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13. ABSTRACT (Maximum 200 words)  Novel Deformation processing of amorphous metals has been conducted on a variety of metallic glasses. Both large scale (e.g. 10's mm size) and small scale (e.g. sub-micrometer size) deformation processing has been conducted using some of the unique properties exhibited by metallic glasses. In all cases, the intermediate temperature properties of metallic glasses (e.g. Zr-, Cu-, Fe-, Al-, Hf-based) have been determined using a NIKON-QM2 Hot Microhardness Machine. Once the effects of changes in test temperature were determined, novel deformation processing of various shapes was conducted. Both fine scale features (i.e. sub-micrometer) as well as larger scale structures were replicated. In addition, the temperature rise near shear bands in bulk metallic glasses was determined using novel nano-scale coatings designed to provide high spatial and temporal resolution. Finally, the fracture toughness of metallic glass/W composites was determined. These materials were processed by others to determine their potential use as advanced penetrator materials.			
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**STATEMENT OF PROBLEM STUDIED:**

Novel Deformation processing of amorphous metals has been conducted on a variety of metallic glasses. Both large scale (e.g. 10's mm size) and small scale (e.g. sub-micrometer size) deformation processing has been conducted using some of the unique properties exhibited by metallic glasses. In all cases, the intermediate temperature properties of metallic glasses (e.g. Zr-, Cu-, Fe-, Al-, Hf-based) have been determined using a NIKON-QM2 Hot Microhardness Machine. Once the effects of changes in test temperature were determined, novel deformation processing of various shapes was conducted. Both fine scale features (i.e. sub-micrometer) as well as larger scale structures were replicated. In addition, the temperature rise near shear bands in bulk metallic glasses was determined using novel nano-scale coatings designed to provide high spatial and temporal resolution. Finally, the fracture toughness of metallic glass/W composites was determined. These materials were processed by others to determine their potential use as advanced penetrator materials.

**SUMMARY OF MOST IMPORTANT RESULTS:**

1. In all cases, the intermediate temperature properties of metallic glasses (e.g. Zr-, Cu-, Fe-, Al-, Hf-based) have been determined using a NIKON-QM2 Hot Microhardness Machine. Although the room temperature hardnesses indicated strength levels approaching theoretical values, there was tremendous softening that occurred upon approaching  $T_g$ , the glass transition temperature.
2. Various shapes were processed at temperatures near  $T_g$  for a Zr-based glass. Both fine scale features (i.e. sub-micrometer MEMS devices) as well as larger scale structures were replicated.
3. The temperature rise near shear bands in bulk metallic glasses was determined using novel nano-scale coatings designed to provide high spatial and temporal resolution. Nano-scale coatings of various low melting point metals were vaopr deposited onto metallic glass substrates prior to fracture. Changes in morphology of the nano-scale coating revealed melting of the coating, indicative of significant temperature rise in the vicinity of shear bands in Zr-, Hf-, and Cu-based metallic glasses.
4. The fracture toughness of metalli glass/W composites was determined on materials supplied by ARL and Liquidmetal. Fracture surfaces were characterized. The fracture toughness was very dependent on the processing conditions and volume fraction of W.

**PUBLICATIONS AND TECHNICAL REPORTS:**

a) Papers Published in Peer Reviewed Journals

1. Wesseling, P., Nieh, T.G., Wang, W.H., and Lewandowski, J.J. (2004). "Preliminary Assessment of Flow, Notch Toughness, and High Temperature Behavior of Cu60Zr20Hf10Ti10 Bulk Metallic Glass", Scripta Mater., 51, pp.151-154.
2. Lewandowski, J.J. and Greer, A.L. (2005). "Temperature Rise at Shear Bands in Metallic Glasses", Nature Materials, in press.
3. Lewandowski, J.J. (2005). "Intrinsic and Extrinsic Toughness of Bulk Metallic Glasses", Scripta Materialia, Viewpoint Set on Metallic Glasses, in press.

b) Papers Published in Non-Peer Reviewed Journals or Conference Proceedings

1. Wesseling, P. Lowhaphandu, P., and Lewandowski, J.J. (2003). "Effects of Superimposed Pressure on Flow and Fracture of Two Bulk Amorphous Metals", in MRS Symposium Proceedings - Volume 754, Supercooled Liquids, Glass Transition, and Bulk Metallic Glasses, (T. Egami, A.L. Greer, A. Inoue, and S. Ranganathan, eds.), MRS, Warrendale, PA, pp.275-280.
2. Wesseling, P., Lowhaphandu, P. and Lewandowski, J.J. (2003). "Hardness Indentation Studies on Metallic Glasses", in MRS Symposium Proceedings - Volume 754, Supercooled Liquids, Glass Transition, and Bulk Metallic Glasses, (A.L. Greer, T. Egami, A. Inoue, and S. Ranganathan, eds.), MRS, Warrendale, PA, pp. 281-286.
3. Lewandowski, JJ, Thurston, AK, and Lowhaphandu, P. (2003) "Fracture Toughness of Amorphous Metals and Composites", in MRS Symposium Proceedings - Volume 754, Supercooled Liquids, Glass Transition, and Bulk Metallic Glasses, (A.L. Greer, T. Egami, A. Inoue, and S. Ranganathan, eds.), MRS, Warrendale, PA, pp. 307-313.

c) Papers Presented at Meetings, but not Published in Conference Proceedings (\*\* Denotes Invited Seminar)

1. \*\*"Pressure/Stress State Effects on Flow and Fracture of Inorganic Materials and Composites", J.J. Lewandowski, University of Cambridge - Dept. Materials Science and Metallurgy, Cambridge, UK, August 20, 2002.
2. "Fracture Toughness of Amorphous Metals and Composites", J.J. Lewandowski, A.K. Thurston, and P. Lowhaphandu, MRS Symposium Supercooled Liquids, Glass Transition, Bulk Metallic Glasses, Boston, MA, December 4, 2002.
3. "Hardness Indentation Studies on Metallic Glasses", P. Wesseling, P. Lowhaphandu, and J.J. Lewandowski, MRS Meeting, Boston, MA, December 2, 2002.
4. "Effects of Superimposed Pressure on Flow and Fracture of Two Bulk Amorphous Metals", P. Wesseling, P. Lowhaphandu, and J.J. Lewandowski, MRS Meeting, Boston, MA, December 2, 2002.
5. \*\*"Fracture and Fatigue of Bulk Glasses", J.J. Lewandowski, California Institute of Technology, Pasadena, CA, January 9, 2003.
6. \*\*"Deformation Behavior of Amorphous Metals", J.J. Lewandowski, WPAFB, Dayton, OH, February 3, 2003.
7. \*\*"Toughness of Metallic Glass and Bulk Metallic Glass", J.J. Lewandowski and P. Lowhaphandu, TMS Spring Meeting, San Diego, CA, March 4, 2003.
8. "Fracture and Fatigue of Amorphous Metals and Composites", J.J. Lewandowski, Liquidmetal, Lake Forest, CA, March 6, 2003.
9. \*\* "Deformation and Fracture Studies on Amorphous Metals", J.J. Lewandowski, Cal Tech DARPA Review Meeting, Washington, DC, March 30, 2003.
10. \*\*"Amorphous Metals-Properties and Performance", J.J. Lewandowski, Lawrence Livermore Nat'l Lab, Livermore, CA, April 30, 2003.

11. \*\*\*"Deformation and Fracture of Amorphous Metals" J.J. Lewandowski, Lawrence Livermore Nat'l Lab Staff Seminar, Livermore, CA, April 30, 2003.
12. \*\*\*"Deformation and Fracture of Amorphous Metals" J.J. Lewandowski, SRI International, Menlo Park, CA, May 1, 2003.
13. \*\*\*"Studies on Metallic Glasses", J.J. Lewandowski, DARPA Review, Arlington, VA, July 7, 2003.
14. \*\*\*"Deformation and Fracture Studies on Amorphous Metals", J.J. Lewandowski, Exxon-Mobil Company, Annandale, NJ, July 22, 2003.
15. \*\*\*"Deformation and Fracture of High Toughness BMG and BMG Composites", J.J. Lewandowski, Composites at Lake Louise, Lake Louise, Canada, October 22, 2003.
16. "Fracture Studies on BMG and BMG Composites", A.K. Thurston and J.J. Lewandowski, Composites at Lake Louise, Lake Louise, Canada, October 23, 2003.
17. \*\*\*"Flow, Fracture, and Fatigue of Bulk Metallic Glass and Composites", J.J. Lewandowski, Gordon Seminar Series, University of Cambridge, UK, October 31, 2003.
18. "Fracture of Bulk Metallic Glass Composites", A.K. Thurston and J.J. Lewandowski, TMS Fall Meeting, Chicago, IL, November 10, 2003.
19. "Fracture and Fatigue of Bulk Metallic Glass", J.J. Lewandowski, Engineering Department, University of Cambridge, UK, November 25, 2003.
20. \*\*\*"Deformation and Fracture Issues in Bulk Metallic Glasses", J.J. Lewandowski, INPG, Grenoble, France, January 6, 2004.
21. \*\*\*"Deformation and Fracture Issues in Bulk Metallic Glasses", J.J. Lewandowski, INSA, Lyon, France, January 7, 2004.
22. "Effects of Mixed Mode Loading on Fracture of Bulk Metallic Glasses", A.K. Thurston and J.J. Lewandowski, TMS Annual Meeting, Charlotte, NC, March 17, 2004.
23. "Novel Deformation Processing of Amorphous Metals", P. Wesseling and J.J. Lewandowski, Research SHOWCASE, CWRU, Cleveland, OH, April 2, 2004.
24. \*\*\*"Bulk Metallic Glasses - Materials of the Future?", J.J. Lewandowski, Postprandial Talk, Churchill College, University of Cambridge, UK, April 23, 2004.
25. \*\*\*"Deformation and Fracture of Bulk Metallic Glasses", J.J. Lewandowski, T. Jacobs, and A.L. Greer, European Physical Society Meeting, Prague, Czech Republic, July 19, 2004.
26. \*\*\*"Flow, Fracture, and Biocompatibility of Bulk Metallic Glasses", J.J. Lewandowski, Dept. Materials Science and Engineering, CWRU, Cleveland, OH, September 21, 2004.
27. "Mechanical Behavior of BMG/BCC Metal Composites", P. Wesseling, A.K. Thurston, P. Lowhaphandu, and J.J. Lewandowski, TMS Fall Meeting, New Orleans, LA, September 28, 2004.
28. "Experimental Observations of Shear Banding in Bulk Metallic Glass", J.J. Lewandowski, N.A. Stelmashenko, and A.L. Greer, TMS Annual Meeting, San Francisco, CA, February 15, 2005.

29. "Ductile vs Brittle Behavior of Metallic Glasses", J.J. Lewandowski, W.H. Wang, and A.L. Greer, TMS Annual Meeting, San Francisco, CA, February 16, 2005.
30. "Effects of Changes in Notch Radius on Deformation and Fracture of a Bulk Metallic Glass", T. Jacobs, J.J. Lewandowski, A.L. Greer, and S. Tin, TMS Annual Meeting, San Francisco, CA, February 16, 2005.
31. "Effects of Superimposed Pressure on Flow and Fracture of BMG's and Devitrified Amorphous Aluminum Alloys", P. Wesseling, L.O. Vatamanu, and J.J. Lewandowski, TMS Annual Meeting, San Francisco, CA, February 16, 2005.
32. "High Temperature Hardness Indentation Studies on Metallic Glasses", P. Wesseling and J.J. Lewandowski, TMS Annual Meeting, San Francisco, CA, February 16, 2005.
33. "Novel Deformation Processing of Amorphous Metal MEMS and Larger Structures", P. Wesseling, A.S. Nouri, and J.J. Lewandowski, TMS Annual Meeting, San Francisco, CA, February 16, 2005.
35. \*\*\*"Flow and Fracture Studies on BMG's and Composites", J.J. Lewandowski, BMG IV, Gatlinburg, TN, May 4, 2005.
36. "Mechanical Behavior of Cu-Based Bulk Metallic Glasses", J.J. Lewandowski, A. Awadallah, P. Wesseling, W.H. Wang, and Y. Liu, MS&T, Pittsburgh, PA, September 27, 2005.
37. "Fracture of Bulk Metallic Glass-W Composites", A. Vormelker, M. Shazly, L. Kecskes, and J.J. Lewandowski, MS&T, Pittsburgh, PA, September 28, 2005.
38. \*\*\*"Flow and Fracture Studies on Bulk Metallic Glasses", J.J. Lewandowski, International Workshop on Flow and Fracture of Advanced Glasses, State College, PA, October 5, 2005.

d) Manuscripts Submitted, but not Published Yet

1. Lewandowski, J.J. and Greer, A.L. (2005). "Temperature Rise at Shear Bands in Metallic Glasses", Nature Materials, in press.
2. Lewandowski, J.J. (2005). "Intrinsic and Extrinsic Toughness of Bulk Metallic Glasses", Scripta Materialia, Viewpoint Set on Metallic Glasses, in press.

e) Technical Reports Submitted to ARO - NONE

PERSONNEL, SHOWING ADVANCE DEGREES EARNED WHILE EMPLOYED ON PROJECT:

Paul Wesseling - MS Degree Awarded  
 Alex Thurston - MS Degree Awarded  
 Ali Shamimi Nouri - Ph.D. Degree in Progress  
 Dr. Luciano Ovidiu Vatamanu - Post Doctoral Worker

REPORT OF INVENTIONS:

Novel Deformation Processing of Amorphous MEMS and Larger Scale Structures - Invention Disclosure